

DFTT 65/94
 hep-ph/9412313
 October 1994

Spin effects in strong interactions at high energy*

M. Anselmino

*Dipartimento di Fisica Teorica, Università di Torino and
 Istituto Nazionale di Fisica Nucleare, Sezione di Torino,
 Via P. Giuria 1, I-10125 Torino, Italy*

Abstract Spin effects in strong interaction high energy processes are subtle phenomena which involve both short and long distance physics and test perturbative and non perturbative aspects of QCD. Moreover, depending on quantities like interferences between different amplitudes and relative phases, spin observables always test a theory at a fundamental quantum mechanical level; it is then no surprise that spin data are often difficult to accomodate within the existing models. A report is made on the main issues and contributions discussed in the parallel Session on the “Strong interactions at high energy” in this Conference.

In the parallel Session on “Strong interactions at high energy” a total of 22 talks were presented on several and various subjects, both theoretical and experimental. As usual, spin effects prove to be unexpected, rich and difficult to understand, testing the deep and basic properties of any theory. In high energy interactions the underlying fundamental theory we are testing is QCD, both in its perturbative and non perturbative aspects; the latter, at least in the energy region so far explored, still play a crucial role, as has emerged from most of the presentations.

Rather than considering the single contributions I have selected the main topics and experimental or theoretical problems discussed in the Session and will try to comment and report on these issues. For more details on the single contributions one is referred to the original talks published in these Proceedings. I apologize with some authors whose contributions will receive

*Rapporteur talk at the XI International Symposium on High Energy Spin Physics, September 15-22, Bloomington, Indiana, to be published in the Proceedings

less attention than others; this is only due to my organization of the material and by no means implies a negative judgement on their work.

The arguments most widely discussed can be divided into:

- 1) pp elastic scattering and total cross-sections;
- 2) single spin inclusive asymmetries;
- 3) hyperon polarization;
- 4) other topics;
- 5) nucleon spin crisis.

The last subject was actually extensively treated in the parallel Session on “Nucleon spin structure functions” to which one is referred; I shall only make here a short comment to answer many questions raised at various stages during the Conference.

pp elastic scattering and total cross-sections

Surprising spin effects in large angle proton-proton elastic scattering at high energy have been known for quite a long time [1, 2]: they concern both single and double spin asymmetries, A , A_{NN} , A_{LL} and A_{SS} . Consider the C.M. scattering of two protons moving along the z -axis and let (xz) be the scattering plane; then the single spin asymmetry A , or analyzing power, is defined as

$$A \equiv \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \quad (1)$$

where $d\sigma^{\uparrow(\downarrow)}$ is the cross-section for the elastic scattering of an unpolarized proton off a proton polarized perpendicularly to the scattering plane, that is along (\uparrow) or opposite (\downarrow) the \hat{y} -axis.

The double spin asymmetry A_{NN} is defined by

$$A_{NN} \equiv \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} \quad (2)$$

where, now, both initial protons are polarized in the direction normal (N) to the scattering plane, as explained for A .

Analogously to A_{NN} , one can define the double spin asymmetries A_{SS} and A_{LL} which only differ from A_{NN} by the direction along which the initial protons are polarized: the S direction is the \hat{x} direction, always choosing (xz) as the scattering plane, and the L direction is along \hat{z} .

A , A_{NN} , A_{SS} and A_{LL} can be written in terms of the five independent helicity amplitudes

$$\begin{aligned} \phi_1 &\equiv \langle ++ | \phi | ++ \rangle \\ \phi_2 &\equiv \langle ++ | \phi | -- \rangle \\ \phi_3 &\equiv \langle +- | \phi | +- \rangle \\ \phi_4 &\equiv \langle +- | \phi | -+ \rangle \\ \phi_5 &\equiv \langle ++ | \phi | +- \rangle \end{aligned} \quad (3)$$

as

$$\begin{aligned}
A &= \Sigma^{-1} \text{Im} [\Phi_5^* (\Phi_4 - \Phi_1 - \Phi_2 - \Phi_3)] \\
A_{NN} &= \Sigma^{-1} \text{Re} [\Phi_1 \Phi_2^* - \Phi_3 \Phi_4^* + 2|\Phi_5|^2] \\
A_{SS} &= \Sigma^{-1} \text{Re} [\Phi_1 \Phi_2^* + \Phi_3 \Phi_4^*] \\
2A_{LL} &= \Sigma^{-1} [|\Phi_3|^2 + |\Phi_4|^2 - |\Phi_1|^2 - |\Phi_2|^2] \\
2\Sigma &= [|\Phi_1|^2 + |\Phi_2|^2 + |\Phi_3|^2 + |\Phi_4|^2 + 4|\Phi_5|^2]
\end{aligned} \tag{4}$$

According to the standard QCD description of large angle exclusive reactions $AB \rightarrow CD$ [3], assuming the dominance of collinear valence quark configurations in the proton wave function, one has the helicity conservation rule

$$\lambda_A + \lambda_B = \lambda_C + \lambda_D \tag{5}$$

which immediately implies, for pp elastic scattering, $\phi_2 = \phi_5 = 0$ and consequently, via Eqs. (4),

$$A = 0 \quad A_{NN} = -A_{SS}. \tag{6}$$

The experimental data [1, 2] do not agree with such conclusions.

All this has been known for quite a long time and several models and attempts to explain the data can be found in the literature. In summary they amount to introduce non perturbative contributions which should still be important at the energies of the performed experiments; quark masses, higher order corrections or intrinsic transverse momenta, which violate the helicity conservation rule, ought to be properly taken into account. Also possible lower energy mechanisms might still interfere with the hard scattering picture and give a sizeable contribution. However, one expects that at higher energies the perturbative QCD predictions should eventually turn out to be correct[†] and further experimental information would be of great importance.

A rich and interesting program for measuring several spin observables in pp elastic scattering and inclusive production is in progress at UNK (Protvino) and RHIC (Brokhaven); reports on the status of the planned experiments can be found in the talks by V. Solovianov, A.M.T. Lin and P.A. Draper.

On the theoretical side it was pointed out in the talk by G. Ramsey how a careful analysis of the data on A_{NN} at the C.M. scattering angle $\theta = \pi/2$, implemented with some reasonable assumptions, might supply information on the scattering amplitudes. $\theta = \pi/2$ is an interesting region in that the data on A_{NN} present a rich structure as a function of the energy and the number of independent amplitudes is reduced to three ($\phi_5(\pi/2) = 0$, $\phi_3(\pi/2) = -\phi_5(\pi/2)$); moreover, one can assume the double-flip helicity amplitude $\phi_2 \simeq 0$.

[†]This need not be true for high energy *small angle* processes, where non perturbative anomalous contributions might persist and remain energy independent in polarization measurements [4]

S. Troshin has presented a model which attempts to explain spin effects via the interference between two phases of QCD, a non perturbative one, described by an effective Lagrangian which allows helicity flips, and the usual perturbative one; such interference is significant in the intermediate energy region of the existing data.

Spin effects are also expected in the measurements of $\Delta\sigma_L(pp) = \sigma_{tot}^{\rightarrow\rightarrow} - \sigma_{tot}^{\rightarrow\leftarrow}$ and $\Delta\sigma_N(pp) = \sigma_{tot}^{\uparrow\uparrow} - \sigma_{tot}^{\uparrow\downarrow}$, the differences between proton-proton total cross-sections in pure longitudinal and normal spin states respectively. $\Delta\sigma_L(pp)$ should be sensitive to the gluon polarization inside the proton (Δg) and any information on Δg is of crucial importance to settle the nucleon spin crisis issue. Some preliminary results on this quantity and, for the first time, on $\Delta\sigma_L(\bar{p}p)$ were reported by D. Grosnick; however, these results are small, consistent with zero, with large errors, and do not allow yet to discriminate between different theoretical models.

Single spin inclusive asymmetries

Large single spin asymmetries have also been observed [5] in the inclusive production of pions in the collision of a high energy polarized proton beam on an unpolarized target, $p^\uparrow + p \rightarrow \pi + X$, where the proton spin is up or down with respect to the scattering plane. These asymmetries

$$A_N(x_F, p_T) = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \quad (7)$$

are found to be large for the transverse momentum of the pion in the range $(0.7 \lesssim p_T \lesssim 2)$ GeV/c and large values of x -Feynman (x_F); actually, $|A_N|$ increases with x_F . A_N also shows interesting isospin dependences ($A_N^{\pi^+} \approx -A_N^{\pi^-}$).

Such results are unexpected because a naive generalization of the QCD-factorization theorem suggests that the single spin asymmetry can be written qualitatively as:

$$A_N \sim \sum_{ab \rightarrow cd} \Delta_T G_{a/p} \otimes G_{b/p} \otimes \hat{a}_N \hat{\sigma}_{ab \rightarrow cd} \otimes D_{\pi/c} \quad (8)$$

where $G_{a/p}$ is the parton distribution function, that is the number density of partons a inside the proton, and $\Delta_T G_{a/p} = G_{a^\uparrow/p^\uparrow} - G_{a^\downarrow/p^\uparrow}$ is the difference between the number density of partons a with spin \uparrow in a proton with spin \uparrow and the number density of partons a with spin \downarrow in a proton with spin \uparrow ; $D_{\pi/c}$ is the number density of pions resulting from the fragmentation of parton c ; \hat{a}_N is the single spin asymmetry relative to the $a^\uparrow b \rightarrow cd$ elementary process and $\hat{\sigma}$ is the cross-section for such process.

The usual argument is then that the asymmetry (8) is bound to be very small because $\hat{a}_N \sim \alpha_s m_q / \sqrt{s}$ where m_q is the quark mass. This originated

the widespread opinion that single spin asymmetries are essentially zero in perturbative QCD.

However, as it has been discussed by several authors [6]-[12], this conclusion need not be true because subtle spin effects might modify Eq. (8). Such modifications should take into account the parton transverse motion, higher twist contributions and possibly non perturbative effects hidden in the spin dependent distribution and fragmentation functions.

An explicit model [8] which takes into account the orbital motion of quarks inside polarized protons or antiprotons and describes meson formation via $q\bar{q}$ annihilation, has been presented by T. Meng, who advocates the use of non perturbative mechanisms to describe spin effects. In this model the different sign of $A_N^{\pi^+}$ and $A_N^{\pi^-}$ simply originates from the $SU(6)$ valence quark spin content of the protons; the results are in qualitative agreement with data and predictions are given for the single spin asymmetry in Drell-Yan processes $\bar{p}^\uparrow + p \rightarrow l^+l^- + X$.

An approach closer to perturbative QCD has been discussed by F. Murgia; application of the QCD-factorization theorem in the helicity basis (for which it has been proved) modifies Eq. (8) into [6]

$$A_N \sim \sum_{ab \rightarrow cd} I_{+-}^{a/p} \otimes G_{b/p} \otimes \hat{\sigma}_{ab \rightarrow cd} \otimes D_{\pi/c} \quad (9)$$

with

$$I_{+-}^{a/p}(x_F, \mathbf{k}_\perp) = \sum_h [G_{h/p}(x_F, \mathbf{k}_\perp) - G_{h/p}(x_F, -\mathbf{k}_\perp)] \quad (10)$$

where h is a helicity index. I_{+-} is a new phenomenological function of relevance for spin observables, analogous to $G_{a/p}(x_F)$ in the unpolarized case; notice that it vanishes when $k_\perp = 0$. A simple model for I_{+-} yields results in very good agreement with the data [13].

This approach has been criticized by Collins [11] on the ground that QCD time-reversal invariance should forbid a non zero value of Eq. (10); he suggests a similar effects in the parton fragmentation process rather than in the parton distribution functions. His criticism is discussed in Ref. [13].

Further theoretical work on spin asymmetries can be found in the talks by G.J. Musulmanbekov, M.P. Chavleishvili and, together with a general analysis of twist-3 single spin observables, by O. Teryaev.

W. Novak has presented a proposal to perform spin measurements at HERA by inserting a polarized target into the unpolarized proton beam. N. Saito has shown the first results on the single spin asymmetry for direct photon production in $p^\uparrow + p \rightarrow \gamma + X$ processes at Fermilab: the results are small, consistent with zero within the large errors, in agreement with the theoretical prediction of Ref. [7].

Hyperon polarization

Hyperon polarization is yet another example of puzzling single spin asymmetry in inclusive processes (mainly $p + N \rightarrow H^\dagger + X$, with unpolarized beam and target); however, it is so well known and so much studied (experimentally) that it deserves attention in its own. Only experimental contributions on the subject have been presented during the Conference; when adding this new information to the previously available one it will become clear why no theoretical interpretation of the data has been attempted.

With some idealization and optimism the bulk of data on hyperon polarization at our disposal up to some time ago could be summarized as:

- all hyperons (with exception of Ω) produced in the proton fragmentation region are polarized perpendicularly to the production plane; antihyperons are not polarized;
- the Λ^0 polarization is negative and opposite to the Σ ;
- the Λ^0 polarization is almost energy independent;
- the magnitude of the polarization increases with p_T up to $p_T \simeq 1$ GeV/c;
- the magnitude of the polarization is independent of p_T above 1 GeV/c and increases linearly with x_F ;
- the polarization depends weakly on the target type (A^α dependence).

Even at such “simple” stage there was no clear theoretical explanation of the data: some semi-classical models could explain some of the features [14] and some other attempts were made which either related the Λ polarization observed in $pp \rightarrow \Lambda X$ to that observed in $\pi p \rightarrow \Lambda K$ [15] or used triple Regge models [16]. However, there is no fundamental explanation of the old set of data and it is very hard to understand how polarized strange quarks, which should be present inside polarized hyperons, can be created in the scattering of unpolarized hadrons.

The situation is now even more hopeless. These are the new data, from Fermilab E761 Collaboration, as summarized by S. Timm:

- antiparticle polarization: anti- Σ^+ and anti- Ξ^- are polarized, anti- Λ is not;
- energy dependence: Σ^+ polarization decreases with energy, Ξ^- polarization increases (in magnitude) and Λ polarization remains constant;
- p_T dependence: Σ^+ polarization decreases above $p_T \simeq 1$ GeV/c;
- x_F dependence: Σ^+ polarization increases with x_F , with a p_T dependent slope, Λ polarization increases (in magnitude) with a fixed slope and Ξ^- polarization is independent of x_F for $x_F \gtrsim 0.4$.

No kind of regular pattern emerges from the data. It is then clear how a successful description of these experimental results cannot originate from general features of the underlying dynamics, but has to rely on subtle non perturbative effects in the hadronization process for each single hyperon.

In the attempt of better understanding the basic mechanisms at work in the quark recombination process the Fermilab E800 Collaboration has measured

the Ξ^- and Ω^- polarization from polarized and unpolarized neutral hyperon beams. The results, presented by K.A. Johns, are, once more, partially expected and partially unexpected.

Other topics

I'll just mention some other talks which dealt with different subjects. The polarization of the J/ψ in pion-nucleus collisions was discussed within perturbative QCD by W. Tang and some spin effects in the production and decay of D^{*+} and Λ_c^+ were studied by R. Rylko. Also a measurement of the Ω^- magnetic moment by the E800 Collaboration was shown by P.M. Border.

A. Brandenburg noticed how the angular distribution of leptons produced in $\pi^- p \rightarrow \mu^+ \mu^- + X$ processes is in disagreement with the standard QCD parton model. A coherent treatment of $q\pi^-$ scattering succeeds in accounting for the data and favours the QCD sum rule pion wave function. A.P. Contagouris has presented a complete computation of higher order corrections for Drell-Yan processes with transversely polarized protons, $p^\uparrow p^\uparrow \rightarrow l^+ l^- + X$ and for $e^+ e^- \rightarrow \Lambda^\uparrow \bar{\Lambda}^\uparrow$.

A simulation for the production of W^\pm and Z_0 in the collision of high energy polarized protons at RHIC, with the aim of measuring the sea polarization, has been discussed by V. Rykov.

Nucleon spin crisis

The nucleon spin structure functions have been discussed in the dedicated parallel Session; however, as many questions were raised during the talks regarding the present situation with the “spin crisis”, I'll briefly comment on that. A comprehensive review on the subject can be found in Ref. [17].

Recall that the measurement of $\Gamma_1^p \equiv \int_0^1 dx g_1^p(x)$, combined with information from hyperon β -decays, allows to obtain a value of a_0 , defined by

$$\langle P, S | \bar{\psi} \gamma_\mu \gamma_5 \psi | P, S \rangle = 2m_N a_0 S_\mu, \quad (11)$$

i.e. the expectation value between proton states (of four momentum P and covariant spin vector S) of the flavour singlet axial vector current $J_{5\mu}^0 \equiv \bar{\psi} \gamma_\mu \gamma_5 \psi$.

In the naive parton model (with free quarks) one has

$$a_0 = \sum_{q,\bar{q}} \Delta q \equiv \Delta \Sigma = 2S_z^q \quad (12)$$

where S_z^q is the total z -component of the spin carried by the quarks; then one expects $a_0 \simeq 1$. Instead, the EMC data [18] yield, at $\langle Q^2 \rangle \simeq 10 \text{ (GeV/c)}^2$,

$$A_0 = 0.06 \pm 0.12 \pm 0.17. \quad (13)$$

Such result, consistent with zero and certainly $\neq 1$, originated the “spin crisis” in the parton model.

However, due to the axial anomaly, we know that $J_{5\mu}^0$ is not a conserved current,

$$\partial_\mu J_5^{0\mu} = \frac{\alpha_s}{4\pi} G_{\mu\nu}^a \tilde{G}_a^{\mu\nu}, \quad (14)$$

so that the expectation value of $J_{5\mu}^0$, $\langle P, S | J_{5\mu}^0 | P, S \rangle$, is scale dependent. Then a_0 is not forbidden to be small at $\langle Q^2 \rangle \simeq 10 \text{ (GeV/c)}^2$ and it might be close to 1 at smaller Q^2 values.

Moreover, this reflects into the fact that there is a gluonic contribution to a_0 , so that what we actually measure at large Q^2 is

$$a_0(Q^2) = \Delta\Sigma - 3 \frac{\alpha_s(Q^2)}{2\pi} \Delta g(Q^2) \quad (15)$$

where Δg is the spin carried by the gluons. Notice that the gluon contribution $\alpha_s \Delta g$ does not vanish when $Q^2 \rightarrow \infty$ as the decrease of α_s is compensated by an increase of Δg . Eq. (15) tells us that $a_0 \simeq 0$ does not necessarily imply $\Delta\Sigma \simeq 0$.

To summarize this brief digression on the nucleon spin problem: a_0 , being the expectation value of a non conserved current, is allowed to evolve in Q^2 , both perturbatively and non perturbatively; there is both a quark and a gluonic contribution to a_0 which, perturbatively, is given in Eq. (15). The large Q^2 perturbative evolution of a_0 is computed to be small ($\mathcal{O}(\alpha_f^\epsilon)$), but the $\alpha_s \Delta g$ contribution does not vanish. The small Q^2 non perturbative evolution may be large and its description requires non perturbative models. The relative amount of non perturbative and Δg contributions is still an open question; in this respect any measurements of the gluon spin would be of great importance.

Conclusions

Needless to say spin effects are fascinating, but tough to understand; in high energy hadronic interactions both the perturbative, short distance physics and the non perturbative, large distance one, are interrelated in subtle and sometime mysterious ways. In order to make successful predictions or even to explain the existing data, we need a knowledge of hadron wave functions, hadronization mechanisms, quark-gluon correlations, and so on, in addition to the usual QCD dynamics. More, detailed and precise spin data are crucial in allowing the work on spin effects to continue; it might be a long and hard work but the eventual outcome – a real understanding of the hadron structure – is certainly worth the effort.

Acknowledgements

I would like to thank the organizers of the Conference and Gerry Bunce for his work and help in the organization of the Session on “Strong interactions at high energy”.

References

- [1] Cameron, P.R., *et al.*, *Phys. Rev.* **D32**, 3070 (1985).
- [2] Crabb, D., *et al.*, *Phys. Rev. Lett.* **41**, 1257 (1978); Crosbie, E.A., *et al.*, *Phys. Rev.* **D23**, 600 (1981); Auer, I.P., *et al.*, *Phys. Rev. Lett.* **52**, 808 (1984).
- [3] See, *e.g.*, Brodsky, S.J., and Lepage, G.P., in *Perturbative Quantum Chromodynamics*, A.H. Mueller Editor, World Scientific (1989).
- [4] Anselmino, M and Forte, S., *Phys. Rev. Lett.* **71**, 223 (1993).
- [5] Adams, D.L., *et al.*, *Z. Phys.* **C56**, 181 (1992); *Phys. Lett.* **B264** (1991) 462; *Phys. Lett.* **B276** (1992) 531.
- [6] Sivers, D., *Phys. Rev.* **D41**, 83 (1990); *Phys. Rev.* **D43**, 261 (1991).
- [7] Qiu, J., and Sterman, G., *Phys. Rev. Lett.* **67**, 2264 (1991).
- [8] Boros, C., Liang, Z., and Meng, T., *Phys. Rev. Lett.* **70**, 1751 (1993); see also the talk by T. Meng in these Proceedings.
- [9] Szwed, J., *Phys. Lett.* **B105**, 403 (1981).
- [10] Efremov, A.V. and Teryaev, O.V., *Yad. Fiz.* **36**, 242 (1982) [*Sov. J. Nucl. Phys.* **36**, 140 (1982)].
- [11] Collins, J., *Nucl. Phys.* **B396**, 161 (1993).
- [12] Artru, X., Czyzewski, J., and Yabuki, H., *Single spin asymmetry in inclusive pion production, Collins effect and the string model*, preprint LYCEN/9423 and TPJU 12/94, May 1994.
- [13] Anselmino, M., Boglione, M.E., and Murgia, F., *Single spin asymmetry for $p^\uparrow + p \rightarrow \pi + X$ in perturbative QCD*, preprint DFTT48/94 and INFNCA-TH-94-27, in preparation.
- [14] Andersson, B., Gustafson, G., and Ingelman, G., *Phys. Lett.* **85B**, 417 (1979); De Grand, T.A., and Miettinen, H., *Phys. Rev.* **D24**, 2419 (1981).
- [15] Soffer, J., and Törnqvist, N.A., *Phys. Rev. Lett.* **68**, 907 (1992).
- [16] Barni, R., Preparata, G., and Ratcliffe, P.G., *Phys. Lett.* **B296**, 251 (1992).
- [17] Anselmino, M., Efremov, A., and Leader, E., preprint CERN-TH/7216/94, to appear in *Phys. Rep.*
- [18] Ashman, J., *et al.*, *Nucl. Phys.* **B328**, 1 (1989).